Constraints on the late X-ray emission from the low-energy GRB 031203: INTEGRAL data

S.Y. Sazonov[1,2], A.A. Lutovinov[1,2], E.M. Churazov[1,2], and R.A. Sunyaev[1,2]

[1] Space Research Institute, Russian Academy of Sciences, Profsoyuznaya 84/32, Moscow 117997, Russia

[2] Max-Planck-Institut für Astrophysik, Karl-Schwarzschild-Str. 1, D-85740 Garching, Germany

Abstract – Comparison of the INTEGRAL upper limits on the hard X-ray flux before and after the low-energy GRB 031203 with the XMM measurements of the dust-scattered radiation at lower energies suggests that a significant fraction of the total burst energy could be released in the form of soft X-rays at an early afterglow stage with a characteristic duration of ∼100-1000 s. The overall time evolution of the GRB 031203 afterglow may have not differed qualitatively from the behavior of standard (i.e., more intense) bursts studied by the SWIFT observatory. The available data also admit the possibility that the dust-scattered radiation was associated with an additional soft component in the spectrum of the gamma-ray burst itself.

1   Introduction

GRB 031203, discovered on December 3, 2003, by the INTEGRAL observatory (Mereghetti and Götz 2003), has attracted much attention because the total energy released during this burst (assuming the radiation to be isotropic) was approximately three orders of magnitude lower than that for standard GRBs. At the same time, the time profile and energy spectrum of the burst were quite normal (Sazonov et al. 2004). The afterglow of this GRB was also weak (Soderberg et al. 2004). GRB 031203 is similar in these properties to another burst, GRB 980425, which was believed to be a unique event before. The similarity of these bursts is also confirmed by the fact that each of them was identified with the explosion of a supernova associated with the core collapse of a high-mass star (Malesani et al. 2004; Galama et al. 1998). Since both bursts were discovered only owing to their relative proximity (GRB 980425 at redshift $z = 0.0085$, Tinney et al. 1998; GRB 031203 at $z = 0.106$, Prochaska et al. 2004), it was suggested that such low-energy bursts could be a more common cosmic phenomenon than standard high-energy bursts (Sazonov et al. 2004; Prochaska et al. 2004).

Additional interest in GRB 031203 is related to the detection of an expanding X-ray halo around the burst position in the sky by the XMM-Newton observatory on the first day after the GRB. This halo was in the shape of two concentric rings. A natural explanation is that this is the soft X-ray radiation from GRB 031203 arrived with a considerable time delay after its scattering by two layers of Galactic dust at a distance of ~1 kpc from the Earth (Vaughan et al. 2004). A careful analysis of the data on the evolution of the halo showed that the X-ray blast that produced it occurred no earlier than ~100 s before and no later than ~1300 s after the GRB (Watson et al. 2006). The estimate (Watson et al. 2006; Tiengo and Mereghetti 2006) of the soft X-ray fluence (at energies ~1 keV) was several times higher than the value obtained by extrapolating the spectrum of the GRB itself that was measured by the INTEGRAL observatory at energies above 17 keV (Sazonov et al. 2004). This raises the question of the origin of the additional soft X-ray radiation. In this paper, we attempt to approach the solution of this question using the upper limits on the X-ray flux before and after GRB 031203 derived from INTEGRAL observations.

2   Observations

We analyzed the data from the IBIS/ISGRI detector (Ubertini et al. 2003) aboard the INTEGRAL observatory (Winkler et al. 2003) that covered the from 21 h 32 min December 3 to 22 h 01 min December 4, 2003, (UT), i.e., half an hour before and a day after the burst. Most of the data were obtained during observations with a stable orientation (~30 min in duration), which alternated with two-minute periods of spacecraft slewing (within a few degrees, so the GRB position always remained within the field of view). Since the IBIS/ISGRI data recording was frequently interrupted during slewing, we also analyzed the data from the SPI spectrometer (with a lower sensitivity than IBIS/ISGRI) for these intervals. This ensured a continuous monitoring of the position of GRB 031203 throughout the period under consideration.

To reconstruct the X-ray light curve of GRB 031203 from the IBIS/ISGRI data, we constructed images of the sky for time intervals from several seconds to one day. We also searched for fast variability (on time scales ~1 s) of the detector count rate within several minutes before and after the burst. Both types of analysis revealed no X-ray radiation from GRB 031203 in the energy ranges 17-25 keV (i.e., just above the detector sensitivity threshold) and 17-60 keV, except for the ~40-s-long burst itself (Figs. 1 and 2). The data on the burst itself were published previously (Sazonov et al. 2004). Given that the observing conditions almost always remained invariable and assuming the radiation spectrum to be identical to that of the Crab Nebula, we

can place (3σ) upper limits on the mean flux from GRB 031203 for interval Δt [s], excluding the GRB and the observatory slewing periods: $\sim 6 \times 10^{-9}(\Delta t)^{-1/2}$ erg cm^{-2} s^{-1} (17-25 keV) and $\sim 8 \times 10^{-9}(\Delta t)^{-1/2}$ erg cm^{-2} s^{-1} (25-60 keV). The corresponding SPI flux limits during slewing are approximately a factor of 5 worse.

The long-term light curve shown in Fig. 2 covers the period in which two series of XMM observations were performed, beginning 6 h after the GRB. Apart from the expanding X-ray halo, these observations revealed a decaying ($f_X \propto t^{-\alpha}$, $\alpha = 0.55 \pm 0.05$) X-ray afterglow of the GRB (Watson et al. 2004). We see from the figure that the INTEGRAL upper limits on the hard X-ray flux are consistent with the XMM flux from the X-ray afterglow at its late stage ($t > 6$ h).

The INTEGRAL upper limits on the hard X-ray flux for the last ~ 100 s before the GRB and the first ~ 1300 s after it (Fig. 1) are of greatest interest, since the bulk of the soft X-ray fluence, which was estimated by Watson et al. (2006) to be $F_X = (2.1 \pm 0.4) \times 10^{-6}$ erg cm^{-2} keV^{-1} at energy 1 keV, was released precisely in this period. The radiation spectrum in the energy range 0.7-6 keV was much softer (a power law with a photon index $\Gamma_X = 2.0 \pm 0.15$) than the spectrum of the GRB itself at energies above 17 keV ($\Gamma = 1.63 \pm 0.06$, see Sazonov et al. 2004). However, it should be noted that the estimated soft X-ray fluence from GRB 031203 is inversely proportional to the optical absorption A_V in the dust layers with which the echo is associated. The above estimate was obtained for $A_V = 2.0$, which is considered to be the most probable one. If the maximum admissible value of $A_V \sim 2.6$ is taken, then the fluence will decrease by $\sim 30\%$ (Watson et al. 2006). An even greater uncertainty is related to the size distribution and other parameters of the dust grains, i.e., to the coefficient τ/A_V at energies ~ 1 keV, where τ is the optical depth of the scattering dust (see, e.g., Draine 2003). This is why Tiengo and Mereghetti (2006) obtained a soft X-ray fluence from GRB 031203 that is approximately a factor of 4 lower than that obtained by Watson et al. (2006) for the same $A_V = 2$ by independently analyzing the same XMM data: $F_X = (3.6 \pm 0.2) \times 10^{-7}$ erg cm^{-2} in the energy range 1-2 keV. Almost the same value was obtained for the spectral slope: $\Gamma_X = 2.1 \pm 0.2$.

Taking into account the significant uncertainty related to the coefficient τ/A_V, we may consider the fluences F_X from the above two papers as the upper and lower limits on the actual value. These limits are shown in Fig. 3 in the same plot together with the INTEGRAL data; more specifically, the GRB spectrum at energies above 17 keV and the upper limits on the fluence in the energy ranges 17-25 and 25-60 keV for any episode with duration $\Delta t = 10$, 100, and 1000 s before or after the burst. It follows from Fig. 3 that if the soft X-ray radiation was released during the GRB, then the GRB spectrum must exhibit an additional soft component (and a deep minimum in the energy range from ~ 6 to ~ 17 keV if the flux normalization of Watson et al. 2006 is correct).

We may also assume that the soft X-ray radiation was released not during the main GRB phase. In this case, we must take into account the fact that the soft X-ray fluence estimated from the observations of the dust echo naturally includes the fraction related to the X-ray radiation during the GRB. This fraction can be estimated by extending the power-law spectrum measured by the IBIS/ISGRI detector to the low energies. Subtracting this fraction changes the estimate of Watson et al. (2006) only slightly: the fluence near 1 keV decreases by $\sim 10\%$, while the effective spectral slope of the soft X-ray radiation increases to $\Gamma_X \sim 2.1$. The extrapolation of this spectrum to the high energies (Fig. 3) passes well above the IBIS/ISGRI upper limits on the fluence in the energy ranges 17-25 and 25-60 keV for $\Delta t \sim 1000$ s and shorter intervals. At the same time, subtracting the GRB contribution decreases the fluence obtained by Tiengo and Mereghetti (2006) by $\sim 30\%$ and increases the effective spectral slope of the soft X-ray radiation to $\Gamma_X \sim 2.4$. This single-power-law spectrum agrees well with our upper limits even at $\Delta t \gtrsim 100$ s.

We cannot rule out the possibility that an X-ray flare with a duration of $\lesssim 100$ s occurred

in the period from 300 to 416 s after the burst, when the INTEGRAL observatory was slewed. There are relatively weak SPI limits on the hard X-ray fluence for this interval. As in the previous case, the soft X-ray fluence and the spectrum obtained by Watson et al. (2006) can be reconciled with these upper limits only if there is a knee in the spectrum in the energy range 6-17 keV. At the same time, the estimate obtained by Tiengo and Mereghetti (2006) does not come into conflict with the SPI limits if the single-power-law spectrum with a slope of $\Gamma_X \sim 2.4$ is extended above 17 keV (see Fig. 3).

3 Discussion

As we noted above, it may well be that the soft X-ray radiation from which the echo on dust was observed in our Galaxy was generated during GRB 031203 itself. This would imply that the GRB spectrum contained an additional soft component at energies below 17 keV. This is atypical of standard GRBs (with a much higher total energy than GRB 031203), whose simultaneous soft and hard X-ray observations usually reveal a softening of the spectrum above a certain energy (Strohmayer et al. 1998; Frontera et al. 2000), as well as for another well-known low-energy burst, GRB 980425, whose spectrum was directly measured in the energy range 2-700 keV by the BeppoSAX observatory (Frontera et al. 2000).

The INTEGRAL and XMM data are consistent with the fact that the bulk of the soft X-ray fluence was released during a prolonged event ($\Delta t \sim$100-1000 s) that occurred slightly later than the GRB. This hypothesis encounters no difficulties if the soft X-ray fluence was close to the value obtained by Tiengo and Mereghetti (2006). In this case, the spectrum could be a single power law with a slope $\Gamma_X \sim$2-2.5 up to high energies (above 17 keV). If, however, the soft X-ray fluence was closer to the value obtained by Watson et al. (2006), then the 6-17 keV spectrum must steepen sharply toward the high energies; otherwise the derived upper limits on the hard X-ray flux outside the burst would be exceeded.

Such a prolonged episode ($\Delta t \gtrsim$100 s) could be associated both with the initial afterglow stage and with an additional, X-ray pulse that followed the GRB. In the last year, the SWIFT observatory has made it possible to systematically study the soft X-ray radiation from GRB sources beginning from ~ 100 s after their detection. In several cases, intense prolonged X-ray flares were actually observed a few minutes after the GRB; these may have been associated with ongoing activity of the central engine (Burrows et al. 2005). Such a scenario is not ruled out for GRB 031203 either, as was noted by Watson et al. (2006). However, most of the GRBs observed by SWIFT have smooth X-ray light curves after $t \sim$100 s (where the time is measured from the burst onset) with a fast flux decay ($f_X \propto t^{-\alpha}$, $\alpha \sim 3$) in the first several minutes followed by an almost flat segment ($\alpha \sim$0.2-0.8), which again gives way to a relatively fast decay several hours later ($\alpha \sim$1-1.5) (Nousek et al. 2005). In many cases, at the initial decay stage, the radiation spectrum below 10 keV is much softer than the spectrum of the GRB itself (measured above $\sim$15 keV by the BAT instrument onboard the SWIFT observatory) and is generally almost constant at the subsequent stages (Goad et al. 2006; Nousek et al. 2005). The soft X-ray fluence released in the interval from ~ 100 s to several hundred seconds after the burst may account for an appreciable fraction of the hard X-ray and gammaray fluence during the burst (Chincarini et al. 2005).

It is possible that in the case of GRB 031203, there was a similar early ($t \lesssim$1000 s) X-ray afterglow stage, when $\sim 20\%$ (if the estimate of Tiengo and Mereghetti (2006) is used) or slightly more of the total GRB was released. This hypothesis is supported by the fact that a plateau ($\alpha \sim 0.5$, Watson et al. 2004) followed by a decay ($\alpha \sim 1.0$, Soderberg et al. 2004) similar to most of the bursts studied by the SWIFT observatory can be clearly distinguished in the light curve for the late ($t > 6$ h) X-ray afterglow of GRB 031203. This scenario is also supported

by the fact that the late X-ray afterglow of GRB 031203 had approximately the same spectrum ($\Gamma_X = 1.90 \pm 0.05$, Watson et al. 2004) as the early X-ray radiation from which the echo was observed.

It should be noted that a relatively slow X-ray flux decay ($\alpha < 1$, Burenin et al. 1999; Tkachenko et al. 2000; Chincarini et al. 2005) was detected in some of the bursts at an early ($t \lesssim 1000$ s) afterglow stage. GRB 031203 may have also had a similar afterglow phase during which the bulk of the soft X-ray fluence was released. However, this phase should anyway be followed by a stage of fast flux decay, since, according to the XMM data, the afterglow intensity 6 h after the burst already fell by several orders of magnitude (see Fig. 2).

References

R.A. Burenin, A.A. Vikhlinin, M.R. Gilfanov, et al., Astron. Astrophys., 344, L53 (1999).

D.N. Burrows, P. Romano, A. Falcone, et al., Science, 309, 1833 (2005).

G. Chincarini, A. Moretti, P. Romano, et al., astro-ph/0506453 (2005).

B.T. Draine, Astrophys. J., 598, 1026 (2003).

F. Frontera, L. Amati, E. Costa, et al., Astrophys. J. Suppl., 127, 59 (2000).

T.J. Galama, P.M. Vreeswijk, J. van Paradijs, et al. Nature, 395, 670 (1998).

M.R. Goad, G. Tagliaferri, K.L. Page, et al., Astron. Astrophys. (2006) (in press).

D. Malesani, G. Tagliaferri, G. Chincarini, et al., Astrophys. J., 609, L5 (2004).

S. Mereghetti, D. Götz, GCN Circ., 2460 (2003)

J.A. Nousek, D.C. Morris, D.N. Burrows, et al., astro-ph/0508332 (2005).

J.X. Prochaska, J.S. Bloom, H.-W. Chen, et al., Astrophys. J., 611, 200 (2004).

S.Y. Sazonov, A.A. Lutovinov, R.A. Sunyaev, Nature, 430, 646 (2004).

A.M. Soderberg, S.R. Kulkarni, E. Berger, et al., Nature, 430, 648 (2004).

T.E. Strohmayer, E.E. Fenimore, T. Murakami, & A. Yoshida, Astrophys. J., 500, 873 (1998).

A. Tiengo & S. Mereghetti, Astron. Astrophys. 2006 (in press).

C. Tinney, R. Stathakis, R. Cannon, et al., IAU Circ. 6896 (1998).

A.Y. Tkachenko, O.V. Terekhov, R.A. Sunyaev, et al., Astron. Astrophys., 358, L41 (2000).

P. Ubertini, F. Lebrun, G. Di Cocco, et al., Astron. Astrophys., 411, L131 (2003).

S. Vaughan, R. Willingale, P.T. O'Brien, et al., Astrophys. J., 603, L5 (2004).

D. Watson, J. Hjorth, A. Levan, et al., Astrophys. J., 605, L101 (2004).

D. Watson, S.A. Vaughan, R. Willingale, et al., Astrophys. J. 636, 967 (2006).

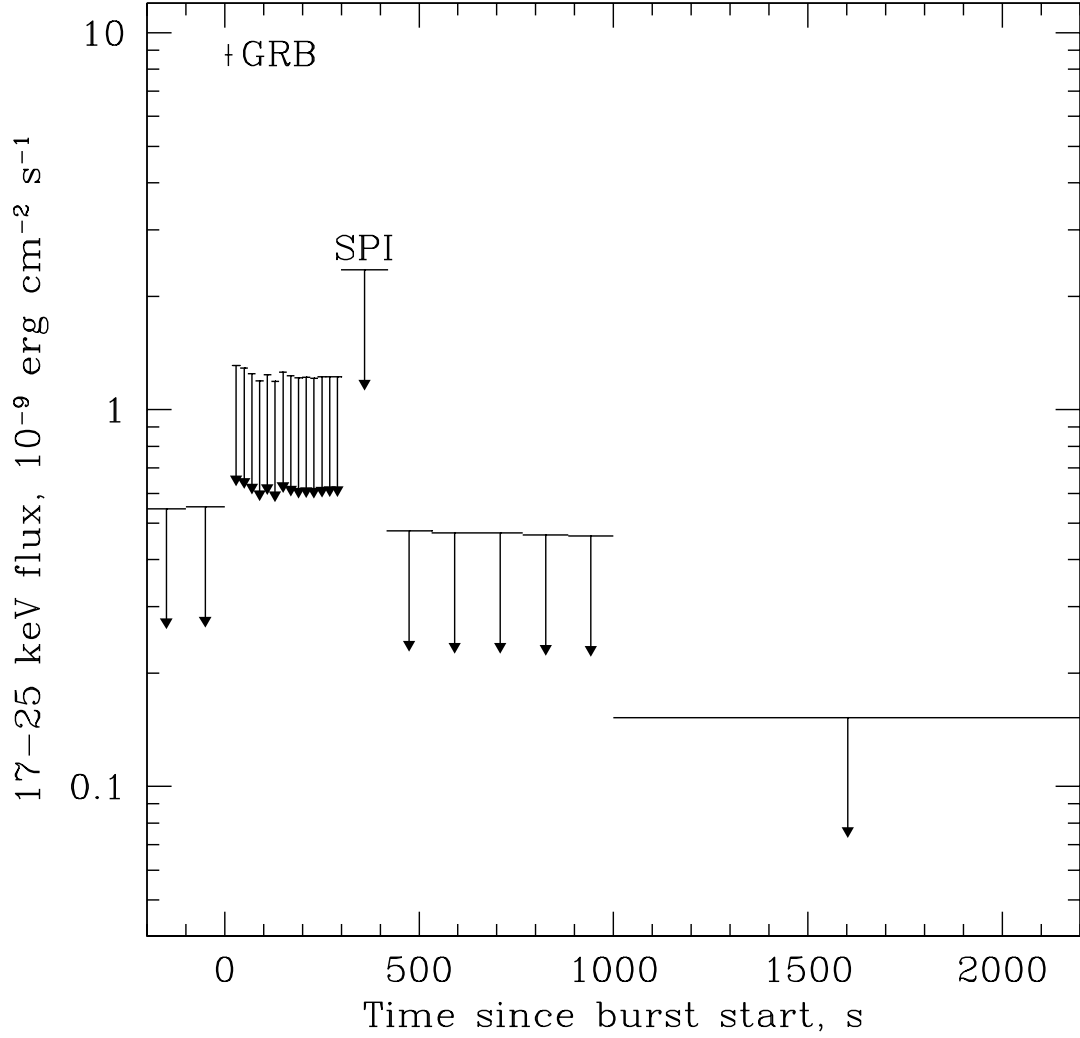C. Winkler, T.J.-L. Courvoisier, G. Di Cocco, et al., Astron. Astrophys., 411, L1 (2003).

Figure 1: IBIS/ISGRI light curve of GRB 031203 in the energy range 17-25 keV in the period from -200 to 2200 s after the GRB onset. The upper limits imply that no flux was detected at a confidence level above 3σ. For the interval 300-416 s in which the observatory was slewed, the SPI upper limit is shown. The point in the interval 0-20 s (labeled GRB) corresponds to the main GRB phase.
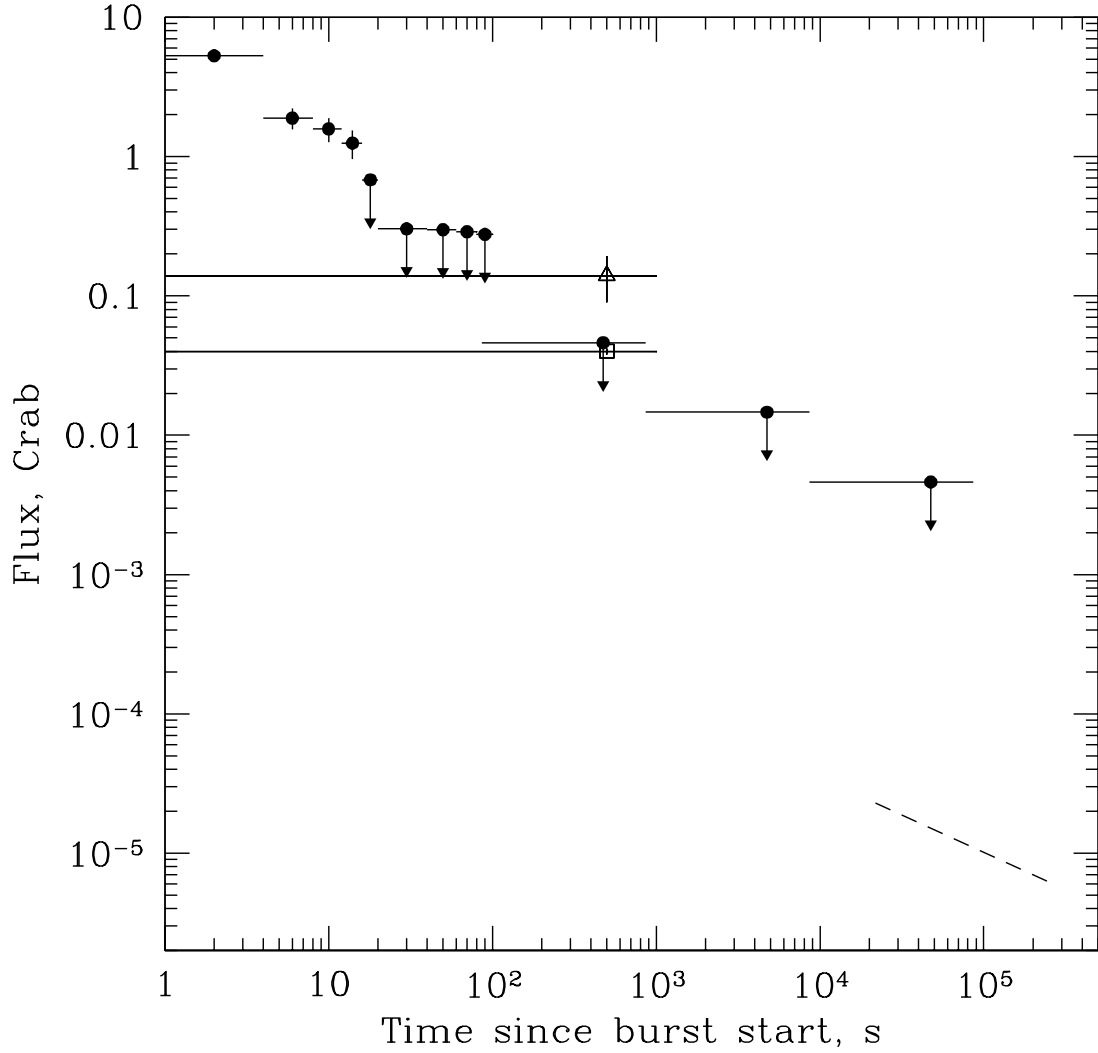
Figure 2: Light curve of GRB 031203 in the energy ranges 17-25 keV (INTEGRAL data, circles) and ~1-5 keV (XMM data, triangle and square) in units of the flux from the Crab Nebula. Two different estimates of the soft X-ray fluence are shown: those from Watson et al. (2006) (triangle) and Tiengo and Mereghetti (2006) (square). These values were obtained by assuming that the X-ray event lasted for $\Delta t = 1000$ s after the burst onset. The dashed line indicates a power-law decay of the X-ray afterglow ($f_{\rm X} \propto t^{-0.55}$) at its late stage (XMM data, Watson et al. 2004). The measurements were corrected for interstellar absorption ($N_{\rm H} \sim 9 \times 10^{21}$ cm^{-2}).
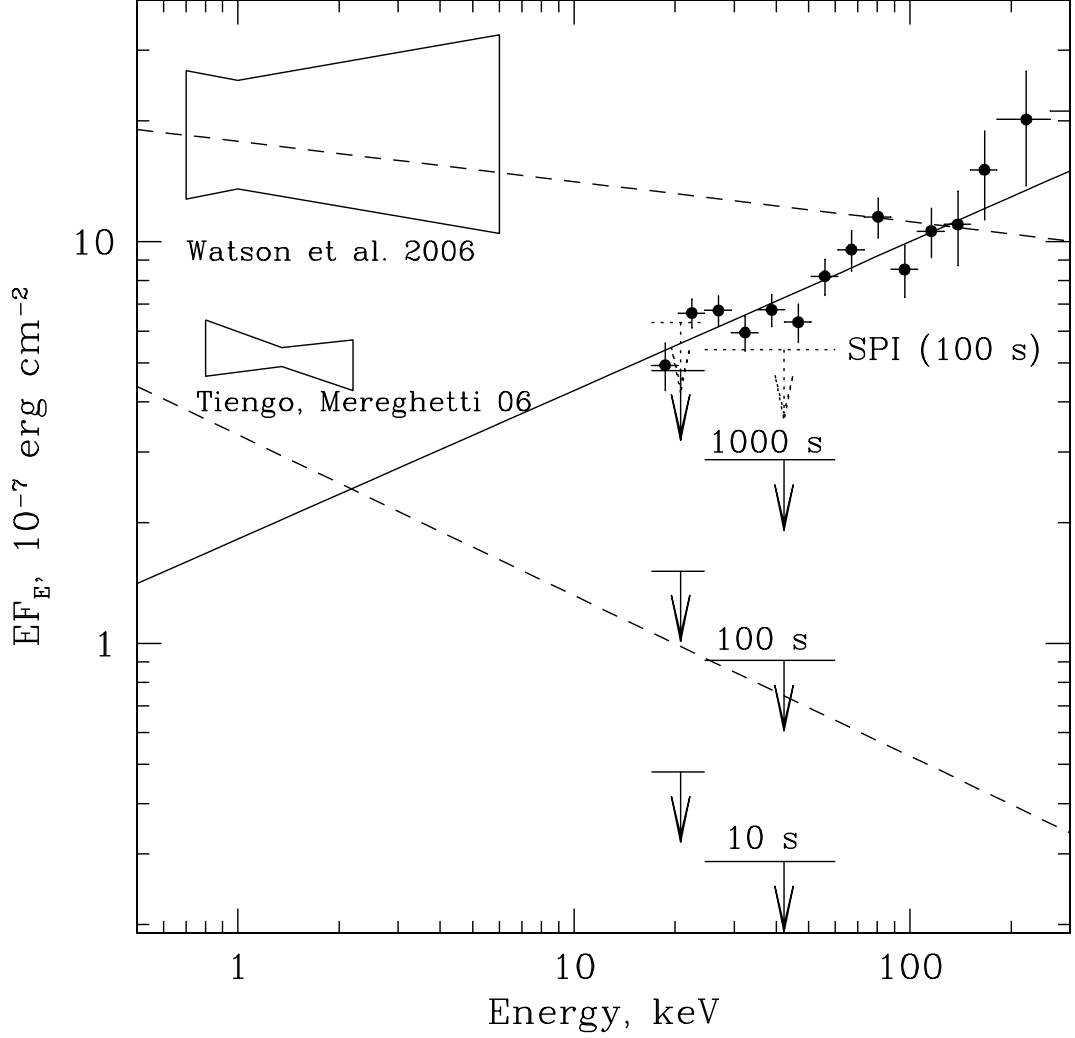
Figure 3: Constraints on the X-ray spectrum from GRB 031203, as derived from INTEGRAL and XMM data. The circles with error bars indicate the IBIS/ISGRI spectrum of the GRB (Sazonov et al. 2004). The solid line indicates the power-law ($\Gamma = 1.63$) best fit to this spectrum extended to the low energies. Also shown are the IBIS/ISGRI (3σ) upper limits on the fluence in the energy ranges 17-25 and 25-60 keV for a time interval of 10, 100, and 1000 s outside the burst, the SPI limit for $\Delta t = 100$ s, and the soft X-ray fluences estimated by Watson et al. (2006) and Tiengo and Mereghetti (2006). The dashed lines indicate the extrapolation of these spectra after the subtraction of the GRB-related radiation.